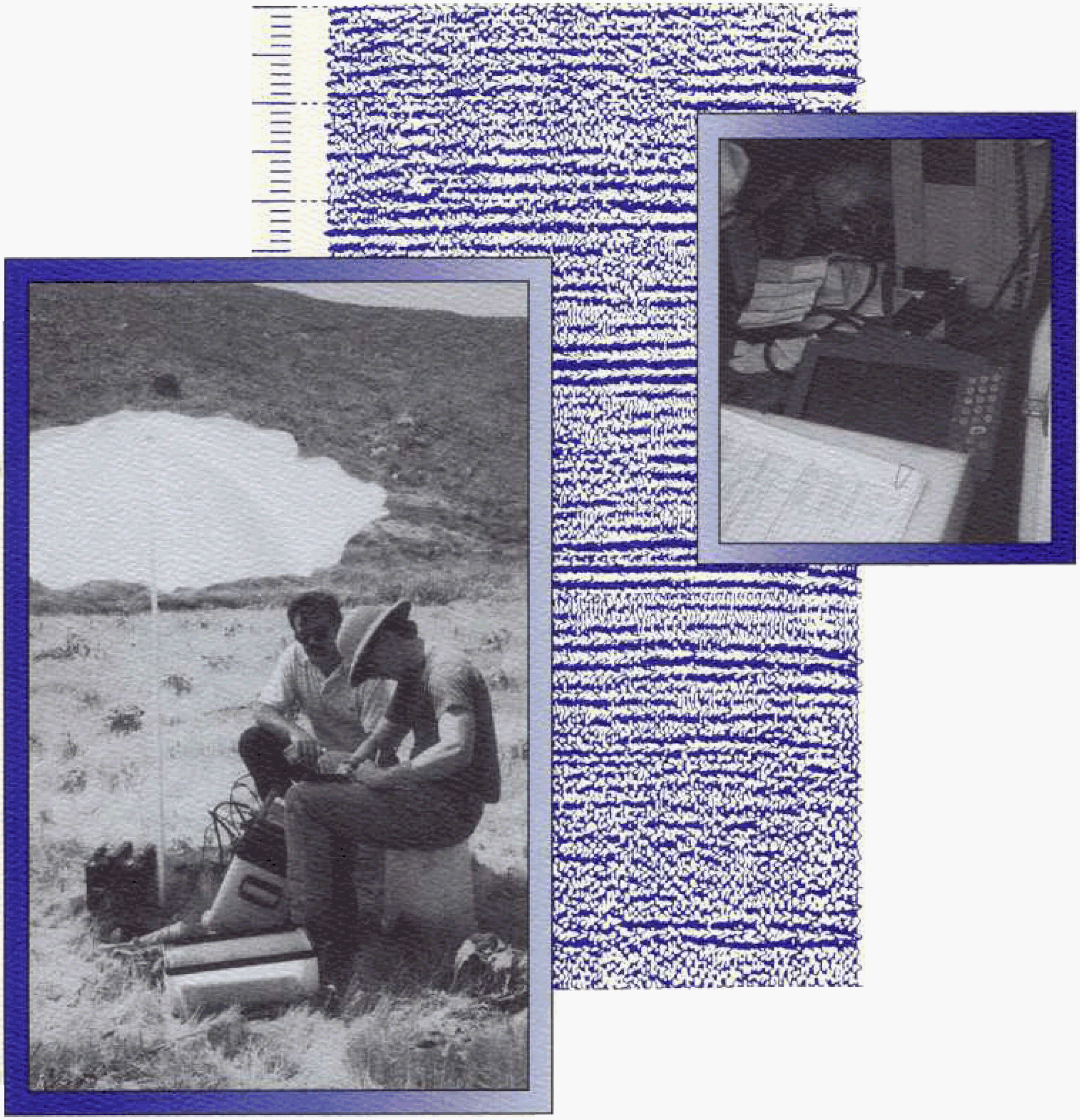
Application of Surface Geophysics at Hazardous Substance Release Sites

Guidance Manual for Ground Water Investigations



State of California
Environmental Protection Agency

APPLICATION OF SURFACE GEOPHYSICS AT HAZARDOUS SUBSTANCE RELEASE SITES

Guidance Manual for Ground Water Investigations

July 1995

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State Water Resources Control Board
Integrated Waste Management Board
Air Resources Board
Department of Pesticide Regulation
Office of Environmental Health Hazard Assessment

FOREWORD

The California Environmental Protection Agency (Cal/EPA) is charged with the responsibility of protecting the state's environment. Within Cal/EPA, the Department of Toxic Substances Control (DTSC) has the responsibility of managing the state's hazardous waste program to protect public health and the environment. The State Water Resources Control Board and the nine Regional Water Quality Control Boards (RWQCBs), also part of Cal/EPA have the responsibility for coordination and control of water quality, including the protection of the beneficial uses of the waters of the state. Therefore, the RWQCBs work closely with DTSC in protecting the environment.

To aid in characterizing and remediating hazardous substance release sites, DTSC had established a technical guidance work group to oversee the development of guidance documents and recommended procedures for use by its staff, local governmental agencies, responsible parties and their contractors. The Geological Support Unit (GSU) within DTSC provides geologic assistance, training and guidance. This document was prepared by GSU staff in cooperation with the technical guidance work group and the RWQCBs. This document has been prepared to provide guidelines for the investigation, monitoring and remediation of hazardous substance release sites. It should be used in conjunction with the two-volume companion reference for hydrogeologic characterization activities:

> ***Guidelines for Hydrogeologic Characterization of Hazardous Substances Release Sites***
> ***Volume 1: Field Investigation Manual***
> ***Volume 2: Project Management Manual***

Please note that, within the document, the more commonly used terms, ***hazardous waste site*** and ***toxic waste site***, are used synonymously with the term hazardous substance release site. However, it should be noted that any unauthorized release of a substance, hazardous or not, that degrades or threatens to degrade water quality may require corrective action to protect its beneficial use.

This document supersedes the 1990 draft of the DTSC *Scientific and Technical Standards for Hazardous Waste Sites, Volume I, Chapter 5,* and is one in a series of Cal/EPA guidance documents pertaining to the remediation of hazardous substance release sites.

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Bill Owen	Hazardous Substances Engineering Geologist,
Steve Belluomini	Supervising Hazardous Substances Engineering Geologist I.

Members of the technical guidance work group participated in the development of this document by providing comments and direction. Additional review and comments were provided by the Regional Water Quality Control Boards and Dennis Parfitt of the State Water Resources Control Board. We thank them for their cooperation and helpful suggestions.

Finally, thanks are extended to the staff of the Geological Support Unit and to the many anonymous reviewers outside DTSC, whose comments were indispensable for completing this document.

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1 INTRODUCTION

1.1 Purpose

This document has been written to provide guidelines for the application of surface geophysical techniques in the characterization of hazardous waste sites. The purpose of this document is to aid in the selection of surface geophysical methods, provide recommended quality assurance and quality control (QA/QC) procedures, and give a standardized approach to the presentation of the resulting data. The recommendations contained herein represent minimal criteria necessary to obtain quality data and assure reasonable and independently verifiable interpretations. The following surface geophysical methods are discussed in this document: seismic refraction, ground penetrating radar, seismic reflection, magnetometry, electrical resistivity, gravimetry, and ground conductivity meters.

As of this writing, the American Society for Testing and Materials (ASTM) is also developing guidelines for surface geophysical techniques. We recognize that guidance developed by a general consensus (such as the ASTM balloting process) are often preferred by the regulated community. It is the intent of the Cal/EPA to incorporate these and other guidelines, where technically and legally relevant, into the Cal/EPA guidance framework. The Cal/EPA is striving to keep up to date with the development of external guidelines, and every attempt has been made to incorporate the intent of those documents into the Cal/EPA guidelines. As new techniques gain acceptance and existing techniques are refined, these guidelines will be updated accordingly to meet the state of the science.

The recommendations presented here are a subset of the larger site characterization process. The additional investigative tools necessary to adequately characterize a site are outlined in Guidelines for Hydrogeologic Characterization of Hazardous Substance Release Sites (Cal/EPA, 1995).

1.2 Application

Surface geophysical surveys are useful for providing information on subsurface geologic and cultural features in areas where limited information exists. When performed properly and utilized early in the site characterization process, surface geophysics can provide valuable information for planning monitoring well and piezometer placement. In addition, surface geophysics can be used to correlate the stratigraphy and hydrostratigraphy between wells, locate buried structures, buried waste containers and, in some instances, can directly detect underground contaminant plumes.

Because the proper use of surface geophysical techniques can significantly reduce the amount of time and cost involved in site characterizations, the California Environmental Protection Agency (Cal/EPA) encourages and recommends the use of surface geophysical surveys wherever feasible. The following guidelines are presented in an effort to promote the use of surface geophysics and increase the overall quality and efficiency of site characterizations throughout the state.

1.3 Limitations

The recommendations presented here represent minimum criteria that can aid obtaining quality data and assuring reasonable and independently verifiable interpretations. Some sites may require investigative efforts above and beyond the scope of this document, while at other sites a less rigorous application of this guidance may be appropriate. It is the obligation of the responsible parties and the qualified professionals performing site investigations to consult with pertinent regulatory agencies, identify all requirements and meet them appropriately.

This document discusses broad categories of methods and instruments that can be used in surface geophysical investigations. It does not define specific operating procedures for conducting geophysical surveys or for interpreting the results. Also, this document does not contain recommendations for every geophysical method and instrument available. The qualified professional in charge of the field investigation should specify the methods, instruments and operating procedures in an appropriate work plan and document any significant departures from the work plan that were necessary during the course of the investigation.

The guidelines presented herein are applicable to the use of surface geophysics to define natural conditions and man-made features that may contain hazardous waste or influence the movement of contaminants. These guidelines are not intended for application to surface geophysical methods used solely to locate underground utilities for drilling and excavation clearance. However, if such utilities are suspected to contain hazardous waste or contribute to waste migration, or if clearing utilities is not the primary objective of the geophysical survey, then this guidance document is recommended.

This document does not supersede existing statutes and regulations. Federal, state and local regulations, statutes, and ordinances should be identified when required by law, and site characterization activities should be performed in accordance with the most stringent of these requirements where applicable, relevant and appropriate.

2 RECOMMENDED PRACTICES AND SPECIFICATIONS FOR SURFACE GEOPHYSICAL INVESTIGATIONS

2.1 Personnel Qualifications

Conducting surface geophysical surveys and interpreting the results requires specialized education and training in physics and geology. Personnel planning field surveys or interpreting geophysical data should possess adequate certification of such training. Specialized geophysical education is not required for field crews conducting geophysical surveys; however, these personnel should be under the supervision of a qualified geophysicist.

The Geologist and Geophysicist Act defines the scope of practice and qualifications for conducting geophysical surveys in California. Section 7835.1 of the Act states "All geophysical plans, specifications, reports or documents should be prepared by a registered geophysicist...registered geologist...or by a subordinate employee under his direction." The registered professional accepts responsibility for the contents by affixing his or her signature or registration seal. However, possession of a state Registration in geology does not, in and of itself, qualify a person to practice geophysics. Therefore, the following criteria should be considered for defining **qualified geophysical personnel:** a Registered Geophysicist for the state of California, or a Registered Geologist for California who is also a **qualified geophysicist,** defined in Section 7807.1 of the Geologist and Geophysicist Act as a person who meets required education and experience qualifications for, but does not possess Registration as a geophysicist. The Cal/EPA recommends that all geophysical studies be supervised and directed by Registered Geophysicists.

2.2 Quality Control Parameters for Geophysical Studies

2.2.1 Feasibility Evaluation and Method Selection

Every surface geophysical technique has specific advantages and limitations. The success or failure of any particular geophysical technique is dependent upon many factors, including geologic conditions, atmospheric disturbances and urban development. It is necessary to evaluate these site-specific factors to assess the viability of surface geophysical techniques and, if possible, select the techniques which will best suit field conditions. Such an evaluation should include the objectives of the study, identify potential sources of interference with the geophysical signal, describe the targets of interest (including composition and depth of burial) and an assessment of sensitivity of the chosen techniques to the targets of interest. The amount and quality of existing site-specific geologic information should also be considered. The number and types of geophysical surveys and measurement locations should be determined by, or in consultation with, qualified geophysical personnel.

A discussion of the feasibility evaluation and its results should be included in an appropriate work plan and site characterization report. This discussion need not be comprehensive: a concise summary may be sufficient for most evaluations. However, the amount of detail should be dependent on site-specific factors and the objectives of the investigation.

2.2.2 Data Processing

Producing interpretable data from geophysical measurements may require some degree of signal processing, to reduce interference caused by noise and enhance the signals of interest. Processing of geophysical data is both art and science, relying on the skills of the operator as well as the capabilities of the processing technique. Care should be used during processing to ensure data of interest to the study are adequately preserved. To this end, data needs should be balanced with processing requirements so that, wherever possible, the amount of processing is kept to a minimum. The processing methods used to produce any final interpretations should be documented in an appropriate site characterization workplan or report. Proprietary techniques should be described, commonly available methods may be documented by reference to peer-reviewed literature.

2.2.3 Measurement Locating

A basic requirement for any site characterization study is that sampling or measurement points be located and mapped accurately. The degree of care and accuracy needed to locate and map geophysical measurements will vary, depending on data requirements and the purpose for their use (for example, gravity measurement stations usually require professional surveying; electromagnetic [EM] measurement stations could be located by simple sighting to a permanent datum, if only qualitative analysis were needed). The techniques and precision of location surveys should be appropriate to the required precision and purpose of the data. If professional surveying is required, civil engineers or surveyors licensed by the state of California should be used. Surveyed points should be recorded using the California State Plane coordinate system. Locations of all measurements should be presented in all appropriate work plans and site characterization reports.

2.2.4 Correlation with Geology

When site-specific subsurface lithologic and hydrologic data are available, the geophysical models should be correlated with the subsurface information. This does not imply that geophysical models may be used by themselves (see Section 2.2.5). If subsurface data are not available, they should be collected whenever feasible. The results of this correlation should be included in the interpretation section of an appropriate site characterization report.

2.2.5 Requirements for Reconnaissance Studies

No geophysical technique yields a unique solution. However, by adding an additional geophysical method to the survey, the number of possible solutions that could fit both data sets is significantly reduced. Without site-specific geologic data, an accurate geophysical interpretation cannot be obtained with confidence. The use of more than one method adds constraint to the geologic interpretation of geophysical data. Therefore, where geophysical techniques are used as part of a reconnaissance study, more than one geophysical technique should be used. For the purposes of this document, a **reconnaissance study** is defined as a study undertaken in the early stages of a site investigation, to plan well or boring installations, removal actions or further investigations at a site where little or no site-specific stratigraphic or hydrostratigraphic information is available.

2.2.6 Calibration and Field Checks

The quality of data from geophysical instruments should be assured through regular calibration and by conducting field checks prior to each survey. All geophysical instruments should be tested and calibrated on a regular basis. Calibration and field checks should be conducted according to manufacturer's recommendations; if none exist, the owner should establish and follow a regular calibration schedule. Equally important is the need for a regular test of instrument function, through the use of regular field checks. Appropriate standards for field checks vary depending on the type of instrument, but can include built-in standards, external calibrators or an established baseline area on the ground. In any case, a description of calibration and field check methods used should be documented and included in an appropriate site characterization report.

2.2.7 Documentation

Procedures for quality assurance and quality control for surface geophysical surveys should be addressed in an appropriate site characterization workplan and report. The workplan should identify the objectives of the study and outline the rationale for the selection of the geophysical methods to be used. The final report should present an interpretation of the geophysical data, and should discuss any problems encountered in the field and any deviations from the workplan that were needed to solve those problems.

As discussed in the preceding sections, the feasibility assessment (Section 2.2.l), measurement locations (Section 2.2.3) and calibration information (Section 2.2.6) should be recorded and presented in an appropriate document. It is equally important that the interpretation of the geophysical data be fully documented and substantiated, for verification and possible extension of the survey. The field methods used to conduct the surveys (Section 2.2.1), techniques used for data processing (Section 2.2.2) and interpretation should be documented in an appropriate site characterization report. All data used to interpret surface geophysical surveys should be presented as part of the interpretation, including a description of regional and (if available) site-specific geology (Section 2.2.4), graphs and tables of geophysical data, and the names and descriptions of any computer software used for data reduction and interpretation. Raw data and data files used for computer modeling need not be included in the final report. However, such data should be kept on file and made available at the request of Cal/EPA. The data and interpretations should be included in one or more deliverables (i.e., work plans and site characterization reports), as described in Guidance for ConductinP Remedial Investigations and Feasibility Studies under CERCLA (U.S. Environmental Protection Agency, 1988).

2.3 Seismic Refraction

Seismic refraction is the predominant seismic method used for engineering and hazardous waste studies. Although use of the seismic reflection technique has increased in recent years for these types of studies, advances in instrument technology and processing techniques indicate that seismic refraction will remain a viable tool (Lankston, 1989).

2.3.1 Profiling Techniques

The quality of seismic refraction interpretations depends on the modeling technique used, the quality of the recorded data and adherence to quality control procedures. The amount and quality of refraction data is partially dependent on the number and placement of shots. Continuous reversed profiling (as described in Telford et al., 1976, pages 363-364) provides optimal shot coverage, and is the predominant profiling method recommended for use. The profile lengths, geophone spacings and shot separations, along with supporting rationale, should be documented in an appropriate site characterization report.

2.3.2 Interpretation Techniques

Many techniques have been proposed for modeling refraction data (Gardner [1939], Mota [1954], and Wyrobek [1956] describe some commonly used interpretation routines). Most of these techniques assume either gently-dipping planar refractors or irregular horizontal refractors with continuous seismic velocities. These routines generally fall into two categories--intercept-time methods (ITM) and delay-time methods (DTM). The main drawbacks to these methods are that the assumptions used in these models, and their inability to accommodate lateral velocity changes, limit their utility to relatively simple geologic structures. The generalized reciprocal method (Palmer, 1980) requires significantly more seismic data, but is superior to the ITM or DTM for modeling irregular dipping refractors and lateral velocity changes; therefore, use of the generalized reciprocal method (GRM) is recommended for refraction modeling of hazardous waste sites. However, ITM's or DTM's may be acceptable for initial site characterization studies, under the following conditions: 1) it can be demonstrated, based on adequate existing evidence, that the strata under investigation are reasonably planar and have dips of less than 10 degrees, or 2) the ITM or DTM models are part of an initial assessment, to be used in planning additional studies.

2.3.3 Equipment Requirements

The choice of seismograph for shallow refraction surveys is important to assuring data quality. Single-channel seismographs are commonly used for some engineering work, and can be adapted for refraction studies. However, single-channel instruments cannot cost-effectively detect seismic interference or determine optimum shot offsets and geophone spacings, all of which can be done easily with multichannel seismographs. Therefore, only multichannel seismographs are recommended for investigations at hazardous waste sites.

2.3.4 Seismic Sources

Seismic refraction surveys at hazardous waste sites are typically limited to depths less than 50 meters. At these shallow depths an adequate seismic signal (shot) can usually be generated by a sledge hammer, weight drop or seismic gun (Benson et al., 1982). For penetration significantly below this depth however, explosive charges are usually required. California law requires a person to be specifically trained and licensed to handle explosives. Therefore, when explosives are deemed necessary for use as an energy source for refraction surveys, all handling of explosives should be performed by a blaster licensed by the California Office of the State Fire Marshal.

2.4 Seismic Reflection

2.4.1 Dominant Seismic Frequency

With the advent of low-cost digital seismographs and more powerful desktop personal computers, the use of seismic reflection techniques for shallow engineering and ground water studies has expanded rapidly. Several important factors should be addressed to assure quality reflection information. Of primary importance is the resolution of the seismic survey. This is dependent on the dominant frequency of the seismic signal. Seismic frequencies used for shallow reflection studies should be above 100 Hz (Hunter et al., 1987). However, the ability to collect high-frequency information may be limited by site conditions beyond control of the investigator. In these circumstances, dominant frequencies below 100 Hz may still yield useful information, but the adequacy of this information should be compared to the actual data requirements on a site-by-site basis. An assessment of dominant seismic frequency should be included in an appropriate site characterization report. This does not always require detailed signal analysis; an estimate of dominant frequency from the raw seismic records should usually be sufficient. However, the amount of detail should be dependent on data needs and the objectives of the investigation.

2.4.2 Equipment Requirements

Signal frequency for seismic work is dependent upon several factors, including the source signal and site stratigraphy. However, the amount of high-frequency data obtained can be optimized by using geophones with natural frequencies above 40 Hz and by filtering the low-frequency component of the signal. Attenuating the low-frequency signals before they are recorded enables preservation of higher frequencies than could be obtained without low-frequency filtering (Knapp and Steeples, 1986; Steeples and Miller, 1990). Therefore, geophones with higher natural frequencies are recommended whenever possible, since they attenuate a broader band of low-frequency data.

The choice of seismograph used for shallow reflection surveys is important to assuring data quality. Single-channel seismographs are commonly used in some engineering studies, and may conceivably be adapted for reflection studies on occasion. However, data from single-channel instruments are not reliable or cost-effective for detecting ground roll and air wave interference, determining optimum shot offsets or performing common-midpoint surveying, all of which can be done with multichannel seismographs. Therefore, only multichannel seismographs are recommended for hazardous waste site investigations. For common-midpoint surveying, greater channel numbers generally improve signal-to-noise ratios. 24-channel seismographs or better are recommended, although 12-channel instruments may be acceptable under optimal site conditions.

2.4.3 Seismic Sources

The energy sources used for shallow reflection work are usually the same as those used in refraction studies. As with refraction work, if explosives are used as an energy source, all handling of the explosives should be performed by a blaster licensed by the California Office of the State Fire Marshal.

2.5 Electrical Resistivity

Electrical resistivity is a widely used surface geophysical technique for hydrogeologic and hazardous waste investigations. The advantage of resistivity techniques lies in the fact that electrical conductance in rocks and sediments is controlled by both matrix mineralogy and the amount of moisture present in the interstitial pores; thus, in many cases resistivity can be correlated to hydrogeology.

There are many different surface geophysical techniques that are based on electrical principles. The most common are induced polarization (IP), resistivity profiling and vertical electrical soundings (VES). Although it is not the purpose of this document to explain the differences and merits of each technique, these methods are quite different in execution and interpretation, and their utility should be evaluated on a site-by site basis (as a simple example, resistivity profiling yields a 2-dimensional interpretation, while VES uses a one-dimensional model; therefore, where cross-sectional information is critical, resisitvity profiling would be the recommended electrical technique). Each method has its particular strengths and weaknesses and should be chosen on a site-specific basis. Ward (1990) has outlined and ranked each technique according to selected performance criteria (Table 1). His paper is recommended as a guide in selecting an appropriate resistivity method.

2.5.1 Equipment Requirements

In the early stages of resistiviity work, soundings and profiling were performed using direct current (DC). However, the use of DC causes undesirable instrument drift due to polarization effects, and are susceptivle to electrical noise from telluric currents and self-potentials. Instrument technology has made it possible to reduce polarization effects through the use of low frequency alternating currents (or commuted DC). The addition of signal averaging, stacking and filtering capabilities has permitted the collection of resistivity data using smaller current sources, resulting in greater portability. These instruments are widely available and are recommended above "pure DC" instruments.

Selection of receiving electrodes is an important factor for environmental surveys. The requirement of low noise is met by several types of porous-pot electrodes, which are discussed in detail by Corwin (1990). The three electrode types in common use (copper-copper sulphate, silver-silver chloride and lead-lead chloride) warrant additional discussion. The primary concern with the use of these electrodes is that the small amounts of electrolyte solutions that lead into the soil during use might result in a "false" hit on a chemical analysis, if the soil is sampled at a later date. This issue has not been studied, but until this question is resolved, the following recommendations should be followed: silver-silver chloride electrodes are the preferred choice; copper-copper sulfate elctrodes are an acceptable alternative, as long as copper is not a contaminant of concern at the site in question; finally, because of potential chronic health effects from handling, in addition to the concern of potential leaking of electrolyte solution, lead-lead chloride electrodes should not be used.

2.5.2 Minimization of Coupling Effects

For resistivity surveys (IP in particular) it is important to minimize the effects of electromagnetic (EM) coupling between transmitter and receiver wires, which obscures the resistivity signal. EM coupling is affected by many factors, including instrument design, electrode geometry and distance between transmitting and receiving wires. Ward (1990) gives a transmitter to receiver wire separation of 100 meters as a typical requirement. Madden and Cantwell (1967) present rule-of-thumb formulas for wire separations as a function of transmitting frequency and wire length. In any case, assessment of EM coupling and measures taken to reduce its effect should be documented in an appropriate site characterization workplan and report.

2.5.3 Equivalence

The problem of equivalence in the inversion of resistivity data has been illustrated by Madden (1971) and Ward (1990). Simply put, equivalence is the principle that multiple combinations of layer resistivity and thickness can be combined to produce the same apparent resistivity measurements. Equivalence is inherent to the method and cannot be overcome; instead, it should be addressed by providing a range of possible interpretations in place of a single solution. For example, Ward (1990) discusses an inversion scheme developed by Rijo et al. (1977) that

Table 1: Evaluation of the three most-commonly used resistivity arrays. Ranking is in order from 1 = best to 3 = worst. Modified from Ward (1990); refer to his paper for a complete description.

Array	Signal to Noise Ratio	Minimization of EM Coupling	Resolution of Lateral Contact	Resolution of Steeply Dipping Structures	Resolution of Horizontal Layers	Insensitivity to Surface Inhomogeneity	
						Sounding Mode	Profiling Mode
Dipole-Dipole	3	1	1	3	2	3	1
Schlumberger	2	2	2	1	1	1	2
Wenner	1	3	3	2	1	2	2

uses the log-normal distribution of data to provide a range of resistivity and thickness values. A minimum of three models should be provided: a best-fit and two additional interpretations that represent reasonable upper and lower limits to the model.

2.6 Ground Conductivity Meters

The term ground conductivity meter (GCM) has been coined by McNeill (1990) to describe a special class of Slingram-type, frequency-domain EM instruments widely used in hazardous waste investigations. EM methods are unsurpassed in their ease of use and ability to investigate large areas quickly and economically. They are therefore the most widely utilized surface geophysical method for hazardous waste investigations. However, GCM's have limitations that should be acknowledged before they are applied at a site. The primary limitations of GCM's are the narrow range of sensitivity, nonlinear instrument response at high ground conductivities, susceptibility of the electromagnetic signal to interference, and sensitivity of some instruments to misalignment. Detection and correction of alignment errors are part of fhe standard operating procedure for GCM's that arp sensitive to misalignment; minimization of interference should be addressed as part of the feasibility evaluation and during data processing (Sections 2.2.1 and, 2.2.2). Therefore, specific guidelines to address these limitations will not be presented.

GCM's currently in use have a stated operating range of 1 to 1000 millisiemens/meter (1000 to 1 ohm-meters) true earth conductivity (McNeill, 1980). However, correction charts supplied by the manufacturer (McNeill, 1983) indicate that above approximately 200 millisiemens/meter (5 ohm-meters), instrument response begins to deviate from true earth conductivity. In this range, GCM readings may be corrected to show true conductivity. Where quantitative data are desired, or when investigating areas of high background soil conductivity, readings should be corrected. However, where background values of earth conductivity are high (significantly above 200 millisiemens/meter), GCM's are not recommended.

Note: Many other EM instruments are potentially available for hazardous waste investigations, such as audio magnetotelluric and Slingram methods. Additionally, very low frequency (VLF) EM instruments have been used in some hazardous waste studies. However, none of these methods have been widely used for hazardous waste investigations; therefore, specific guidelines for them will not be developed. Time-domain EM is a technique that, due to recent advances, may show promise for environmental studies, though its use is currently limited. As experience with this technique grows and its effectiveness becomes known, guidelines may be eventually developed for this method.

2.7 Ground Penetrating Radar

Ground Penetrating Radar (GPR) is a valuable tool for surface geophysical investigations. With GPR, data can be collected rapidly and interpreted while still in the field, and its ease of interpretation is matched only by seismic reflection techniques.

As with any other geophysical technique, GPR has limitations. The resolution of radar data is partially dependent upon signal density. The predominant radar instrumentation for hazardous waste studies uses pulsed microwaves; therefore signal density is dependent on both the pulse rate and the speed of traverse. In any case, to optimize the high resolution inherent to GPR, signal density should be no less than ten pulses per meter.

GPR often cannot penetrate significantly below the water table, since depth of penetration is adversely affected by increasing moisture content. Therefore, GPR surveys are usually not feasible during or shortly after rainstorms. To minimize the effects of near-surface moisture, GPR should not be performed after any measurable precipitation until the ground has sufficiently dried.

Like EM techniques, GPR is susceptible to external interference. Trees, power lines, radio transmissions and surface debris can significantly affect radar images (Benson et al., 1982). Sufficient care should be taken to minimize this noise, through the use of shielded antennae, appropriate operating procedures and signal processing as needed.

The guidelines presented in this document were developed for ground-based, pulsed microwave GPR systems. Continuous-wave and airborne pulsed wave instruments do exist, but their availability is extremely limited, or they are still considered experimental. As new GPR techniques and instruments are developed and gain acceptance, these guidelines will be updated as necessary.

2.8 Magnetometry

Magnetometric methods have been used with great success in mineral and petroleum exploration; however, magnetometry has limited practicality for geologic investigations of hazardous waste sites. Because of the extreme sensitivity of the Earth's magnetic field to micro-scale anomalies, magnetometry works best in rural or unpopulated areas. Urban development introduces innumerable sources of noise: fences, power lines, underground pipes, even small pieces of buried metal debris can cause local perturbations in the magnetic field. However, these sources of magnetic noise are themselves often items of interest, because localized magnetic anomalies at hazardous waste sites are often directly associated with hazardous waste disposal. This is typically not caused by the waste itself, but by the containers in which the waste was placed. Buried steel drums and pipelines, as well as metal debris associated with waste can be readily detected by magnetometry. Thus, magnetic noise that masks the geologic signal is often a valuable target for geophysical surveys at hazardous waste sites.

Base Station Requirements

For most hazardous waste studies, magnetic anomalies of interest are often one to two orders of magnitude greater than the natural variations in the magnetic field (diurnal variations and micropulsations). However, if the signal associated with buried wastes is expected to be within the range of the natural field variation, two magnetometers are needed: one to record field information, the other to record baseline measurements. The data from this base station should be used to check for magnetic storms, measure diurnal variations and correct the field data. A discussion of the data quality, corrections and unusual magnetic events from the base station record should be presented in an appropriate site characterization report.

2.8.2 Repeatability

Undertaking magnetometric surveys at hazardous waste sites requires a considerable degree of care and preparation. Wherever possible, the locations of all utility lines (both above and underground) should be determined beforehand. In addition, if the anomalies of interest are expected to be of similar magnitude to the natural field variation, it is necessary to assess site-specific noise and instrument repeatability by taking at least two readings at each measurement station. Repeated measurements should agree to within 1 gamma (or the minimum accuracy of the instrument). Field measurements that do not repeat to within this value should be averaged. Values that do not repeat to within 10 gammas should not be used. During magnetic storms, when large variations in the magnetic field occur, such repeatability is usually not possible. While these conditions persist, magnetic surveys should not be undertaken.

Note: These guidelines were developed for ground-based, total field instruments. The above guidelines do not generally apply to the use of gradient-type magnetometers (gradiometers). Airborne magnetometers have been extensively used for resource exploration, but except for very large, remote sites where regional geology or isolated cultural features (e.g., landfills, buried wells) are of interest, aerial magnetometry is not suited for hazardous waste investigations. We do not foresee any significant change in the use of aerial versus ground magnetometry; however, if magnetometer technology and processing techniques advance to the point where aerial magnetometry becomes viable for hazardous waste investigations, guidelines will be developed accordingly.

2.9 Gravimetry

Gravimetry is not routinely used for hazardous waste investigation, primarily because gravimetric techniques are typically not sensitive enough to detect buried hazardous waste or waste-related features. Microgravity methods exist that increase resolution of small shallow targets, but these methods are difficult to implement or costly when compared to other geophysical methods of equal effectiveness. Guidelines for microgravity surveys will therefore not be developed. However, gravimetry is still a useful tool for larger scale investigations related to hazardous waste sites. Therefore, the guidelines presented here are applicable to the use of gravity methods to delineate geologic structures and other large-scale features, such as faults, landfills and ground water basins potentially contributing to or affected by pollution.

2.9.1 Survey Procedures

Considerable care needs to be exercised when conducting gravity surveys and reducing the acquired data. Gravimeters are susceptible to erratic changes in instrument readings (tares) if improperly handled or jarred. In addition, gravimeters are prone to instrument drift due to aging and temperature changes. The degree to which these effects occur depends on the design of the gravimeter. Careful handling and assuring a constant instrument temperature are essential to the success of any gravity survey.

Numerous survey methods exist that allow for tare checks and drift correction. All follow some variation of a technique presented in Telford et al. (1976), in which stations are measured along a loop, resulting in a periodic remeasurement at selected stations. We recommend, as proposed in Telford et al., that stations be reoccupied at intervals not to exceed two hours. To permit data correction, the time of each gravity measurement should be recorded. Drift data will contain components of both instrument drift and tidal effects. For most surveys both effects can be removed using the drift data alone; however, for high precision work the tidal effects should be removed using accepted tide-correction formulas (L.J. Barrows, personal communication).

The possibility of tares complicates matters. If during the course of a survey a gravimeter is subjected to a jarring force beyond that which occurs during normal handling, the operator should check for instrument tares by repeating gravity measurements at the last station prior to the suspected tare. In spite of this precaution, tares may not be detected until drift between stations is checked. An unusually large drift indicates a tare has occurred. This condition invalidates that particular loop, requiring re-measurement. The corrections applied to the measurements and the amount of tide-corrected drift should be documented in an appropriate site-characterization report.

The quality of the gravity measurement should also be assessed. In the newer generation of automated instruments repeatability is quite good, and measurement quality can be assessed by examination of the tide corrected drift. Older instruments are more susceptible to measurement error. For these meters, repeatability should be checked by taking two or more readings at each station. These readings should agree within the limits of precision required for the survey.

2.9.2 Terrain Corrections

Corrections for terrain changes are necessary because nearby differences in elevations can decrease the gravity measured at a station. The most common method of removing this unwanted signal uses the Hammer terrain correction charts (Hammer, 1939). In this system, the gravity effects of successive concentric rings surrounding the station are summed. The advent of digital elevation models (DEM's) have made the task of terrain corrections much easier. Initially limited to corrections distant from the measurement station, the availability of newer detailed DEM's from the U.S. Geological Survey now permits automated corrections within 5 to 45 meters of the station (Cogbill, 1990). The amount of correction is dependent on both the sensitivity of the instrument and the degree of accuracy required for any particular site. The method of correction should be documented in an appropriate site characterization report.

Note: The terrain correction is but one of several corrections that should be made to obtain interpretable gravity data. A cogent proposal for standardization of gravity corrections has been proposed by LaFehr (1991). We recommend his paper for additional information.

2.9.3 Measurement Locating

Other factors important to a successful gravity survey are the accuracy of station location and choice of base station. Gravity base stations should be tied to the California Gravity Base Station Network (Chapman, 1966) or other recognized network (such as the U.SGeological Survey or the Defense Mapping Agency base station networks). Base stations should be reoccupied on a regular basis. Current instrument sensitivities are on the order of 0.01 milligals (10^{-5}cm/s2). To match this sensitivity, measurement stations should be accurately located both vertically and laterally (a survey accuracy of 0.01 mgal requires elevation control of better than $\underline{+2}$ inches [L.J. Barrows, pers. commun.] and lateral control to better than $\underline{+30}$ feet [Telford et al., 1976]). Global positioning system (GPS) measurements are also acceptable where high accuracy is not required. Measurement points should be surveyed to within tolerances necessary to match the required precision of the gravity measurement. The data needs and resulting accuracy requirements for the location surveys should be assessed and documented in an appropriate work plan.

Note: These guidelines have been developed for ground-based gravity instruments. Marine and airborne gravity meters exist and are in use, but their resolution is not judged sufficient for hazardous waste work. Therefore, recommendations have not been developed for these other instruments.

3 SUMMARY OF GUIDELINES

The following outline is presented to summarize the important points presented in this document.

PERSONNEL OUALIFICATIONS

1. Should use a Registered Geophysicist or a Registered Geologist who is also a qualified geophysicist (as defined by the Geologist and Geophysicist Registration Act).

OA/QC PARAMETERS

1. Define study objectives, assess feasibility and select geophysical methods on a site-by-site basis.
2. Document processing techniques applied to geophysical data.
3. Accurately locate geophysical measurement points.
4. When available, correlate geophysical data with geologic information.
5. For reconnaissance studies, use more than one geophysical technique.
6. Follow regular calibration procedures
7. Perform field checks using appropriate standards.
8. Provide supporting documentation for geophysical interpretations.

SEISMIC REFRACTION

1. Utilize continuous reversed profiling techniques.
2. The Generalized Reciprocal Method is preferred over other interpretation schemes.
3. Use multichannel seismographs.
4. All handling of explosives should be performed by a licensed blaster.

SEISMIC REFLECTION

1. Utilize dominant seismic frequencies above 100 Hz.
2 Use multichannel seismographs and geophones with natural frequencies 2.40 Hz.
3. All handling of explosives should be performed by a licensed blaster.

ELECTRICAL RESISTIVITY

1. Utilize alternating current instruments.
2. Use silver-silver chloride or copper-copper sulfate electrodes.
3. Observe appropriate techniques to minimize EM coupling effects.
4. Address equivalence by providing a range of possible interpretations.

GROUND CONDUCTIVITY

1. Correct raw readings for quantitative analysis.
2. Use of GCM's is not recommended in areas of high conductivity (significantly above 200 millisiemens/meter).

GROUND PENETRATING RADAR

1. Keep signal density $\geq$ 10 pulsedmeter.
2. After any precipitation, allow ground surface to dry before performing survey

MAGNETOMETRY

1. Use base stations and repeat measurements when measuring small signals.
2. Magnetometer surveys should not be performed during magnetic storms.

GRAVIMETRY

Reoccupy field base stations at regular (< 2 hour) intervals.
2. Repeat measurements affected by instrument tares.
3. Perform data corrections and survey measurement locations to a degree of accuracy commensurate with the accuracy of the gravity measurement.

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